**ORIGINAL ARTICLE**

# Land suitability modelling for rainbow trout farming in the Eastern Himalayan Region, India, using GIS–MCE approach

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## Abstract

In light of India's extensive cold-water resource base, cold-water fish farming, particularly for rainbow trout, is one of the country's most promising industries. The output potential has not yet been fully realised, despite the recent increase in production. To expand horizontally, the conventional technique is used, which opens up the possibility for more cross-sectoral conflicts to escalate. Thus, a geographic information system (GIS)-based model has been designed for rainbow trout aquaculture in Tawang, Arunachal Pradesh, India, considering the wise and sustainable utilisation of cold-water resources. Fourteen critical criteria were identified for site selection based on topography, water quality, and infrastructure facilities. Analytical hierarchical process (AHP) was used to create sensitive enough peer-to-peer comparison matrices for the selection process, allowing each criterion to be given a specific weight. Data from the Shuttle Radar Topography Mission (SRTM DEM-30 m) satellite were analysed for elevation and slope characteristics. Landsat 8 (OLI) data were employed to classify the current land use pattern. Based on a field survey and secondary data, the GPS locations of infrastructure facilities, like market-places, hatcheries, etc., were marked to delineate them. Using a geographical information system–multi-criteria evaluation (GIS–MCE) approach based on a weighted map overlay, we found that 0.14% (340.21 ha), 0.77% (1810.98 ha) and 0.02% (50.70 ha) of the region is most suitable, moderately suitable and least suitable, respectively, for rainbow trout farming. This model will facilitate the equitable distribution of available resources and give policymakers and other interested parties a common ground to build practical plans for the growth of cold-water aquaculture in the region.

## Introduction

Currently, India produces 14.16 MMT of fish annually, with a 73.65% share from the inland sector, including aquaculture (DAHDF 2019–20). Although aquaculture growth has shown many strides over the years, much more needs to be done to tap the enormous potential the sector has to offer with due care to environmental impacts. Off late, the capture fishery has been showing a declining trend, increasing the dependency on aquaculture through enhanced fish production to meet the protein requirements. Despite its rapid growth in the last few decades, the progression rate is hindered by many factors, such as limited identified suitable sites, poorly selected sites, sectorial conflicts, possible environmental concerns, and legal issues. Sustainable use of natural resources can only be achieved through a proper aquaculture development framework; otherwise, the resources' overexploitation and unsustainability are bound to occur. Concurrently, suitable site identification is crucial for aquaculture operations in a sustainable manner. This will minimise the environmental risks, reduce the multi-use resource conflict, and maximise the production and economic returns (GESAMP 2001).

Since creating a new aquaculture facility primarily involves converting existing land use patterns, it has its corresponding social, legal and environmental implications (Alonso-Perez

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et al. 2003). Thus, site selection requires a thorough knowledge of the existing land usage and pattern, natural resources available, slope gradient of the region and, notably, the existing legal framework (MoEF 1972, 1986). In the coming days, land availability for aquaculture expansion and enhancement will be the critical and limiting factor for sustaining its growth (OECD-FAO 2013). Resource usage and development have categorical spatial dimensions; to make development sustainable, a framework must comply with the spatial and temporal dimensions affecting sustainability (Frankic 2003). Over the last few decades, the scientific fraternity has developed tools and methodologies to address such issues. However, there is an utmost need to focus on and direct these tools to the industry and management. Geographic information system (GIS) in association with remote sensing is a promising and practical tool for planning due to its ability to visualise those extensive data assessments (McLeod et al. 2002). These can also be used to define the geographic framework, identify resource limitations, and specify the environmental constraints (Stead et al. 2002).

In most applications, remote sensing finds its role as a data source in GIS analysis. This technology reduces the envisaged sampling effort and widens the spatial and temporal coverages of estimation. The principal element of the GIS is the use of a location referencing system so that data about a specific location and its attributes can be compared to other locations (Burrough and McDonnell 1998). This technology is also helpful in facilitating the decision-making process for hill planners concerning aquaculture. The uses of GIS and remote sensing in planning for aquaculture development, together with selected cases, have been documented (Meaden and Kapetsky 1991; Nath et al. 2000; Kapetsky and Anguilar-Manjarrez 2007). A number of studies have been carried out involving remote sensing and GIS for aquatic resource mapping and aquaculture siting in different parts of the globe. such as catfish farming development (Kapetsky et al. 1988); brackishwater aquaculture site selection of the Andaman and Nicobar group of islands (Bahuguna et al. 1995); Hard clam culture in Florida (Arnold et al. 2000); Scallop culture in Sungo Bay, China (Bacher et al. 2003); shrimp farming in Vietnam (Giap et al. 2005); brackishwater site selection in Maharashtra India (Karthik et al. 2005); shrimp and crab farming in Bangladesh (Salam et al. 2003); carp farming in Bangladesh (Salaam et al. 2005); urban aquaculture development in Bangaldesh (Hossain et al. 2009); oyster farms in Geoje-Hansan Bay, Korea (Cho et al. 2012); identifying potentially suitable sites in lake Tana basin, North-west Ethiopia (Assefa and Abebe 2018); mapping coastal lagoon characteristics for the aquaculture suitability in south east India (Jayanthi et al. 2021).

Hadipour et al. (2015) applied geographic information systems (GIS), the AHP method, and MCDM to identify areas that are suitable for shrimp aquaculture development in coastal area of Hormozgan, Iran. To create models, a

combination of layers was carried out through Boolean operators and weighted linear combination (WLC) method. The model evaluation results revealed that the most of the areas classified suitable in WLC model coincide with the existing shrimp farms and this indicates the validity of the GIS-based WLC model. To improve resource management strategies that are vital to ensure sustainable fish stocks in the region, Nayak et al. 2018 carried out investigation in the Himalayan region to assess the soil, water and infrastructure facilities by using geographical information system (GIS) and multi-criteria evaluation modelling. Sixteen (16) thematic layers were prepared using the Geomedia Professional software to develop a series of GIS models/ sub-models using the soil, water and infrastructure facilities characteristics of the region assessed thoroughly by analytical hierarchy process (AHP) for development of fish culture. The authors finally categorised the region into different suitable locations for the development of highland and lowland fishery. Esmaeilpour-Poodeh et al. (2019) employed the weighted linear combination modelling (WLCM), for identification of suitable sites for sturgeon cultivation in the southern coast of the Caspian Sea, Golestan Province, Iran. The criteria were categorized into three groups/sub-models: environmental, infrastructural and water resources. Multi-criteria evaluation (MCE) and analytic hierarchy process (AHP) techniques were utilised to determine the effect and weight of each criterion. The map layers were fuzzy based using the expert opinions and sturgeon's characteristics. The final map was generated using the WLC approach. The authors identified that factors such as distance to water resource and distance to roads, industrial and residential areas have had the highest effect on the process of site selection for sturgeon farming. Fifteen key criteria (socio-economic, environmental and physicochemical) were identified for the development of the suitability of land for sustainable rainbow trout aquaculture in the Molinopampa district (Peru) using remote sensing and GIS (Calle Yunis et al. 2020). AHP and MCE approach were utilised in assigning weights to selected criteria. The weighted overlay approach was used in final site selection, which was categorised into very suitable", "moderately suitable" and "marginally suitable", respectively, for the development of aquaculture. The authors believe that the implementation of this methodology will contribute to more effective investment planning and efforts, both by the government and by private industries. In another study, Ghobadi et al. 2021 investigated the possibility of aquaculture development in Lorestan province using GIS-based DANP. A total of 21 criteria were classified into three dimensions: water quality, soil quality and infrastructural and land use for site selection analysis. The criteria were weighted using the ANP method, while the relationship between criteria was considered by the DEMATEL method. In the final suitability map, the region was categorised into best suitable, the moderately suitable

and the least suitable areas for aquaculture development. Bandira et al. 2021 integrated a geographic information system and multi-criteria evaluation approach in identifying the potential sites for brackish aquaculture in the George Town Conurbation, Malaysia. The criteria used were spatial data such as current land use, environmentally sensitive data, and soil quality data of the region. The selection was undertaken in ad hoc manners based on available land identified by aquaculture operators. The results indicated that the George Town Conurbation has a minimal potential site (0.37%) for aquaculture sites. Ordered weighted averaging (OWA) methodology was employed in identifying suitable area for marine aquaculture in Caspian Sea (Iran) with an attempt to introduce the concept of risk in GIS-based analysis (Haghshenas et al. 2021). Eighteen modelling criteria (14 factors and 4 constraints) were considered to determine the appropriate areas for marine aquaculture. Six (6) scenarios using multi-criteria evaluation (MCE) and ordered weighted average (OWA) methodologies were created to achieve the goal. The authors further affirm through sensitivity analysis that social–economic, water quality, and physical–environmental parameters were the sensitive parameters. Furthermore, based on Cramer's V coefficient values for each parameter, bathymetry and distance from the coastline were the most effective and maximum temperature had the least impact on-site selection of marine aquaculture.

From the above, it is clear that most studies applied multi-criteria evaluation (MCE) techniques to connect individual criteria using additive or multiplicative models—with or without weights to indicate the importance of factors and obtain a suitability index or score for sites. Results typically take the form of suitability maps that designate the spatial distribution of areas with different levels of suitability for aquaculture production. Finally, MCE in combination with GIS helps to improve the quality of planning and decision-making process (Vafaie et al. 2012).

The state of Arunachal Pradesh lies in the north-eastern part of the Himalayas, bounded by Bhutan in the west, China in the north and north-east and Myanmar in the east. The state stretches from snow-capped mountains in the north to the plains of Brahmaputra valley in the south (https://arunachalpradesh.gov.in). The state has numerous aquatic resources in the form of upland lakes (2500 ha), riverine resources (2000 km), ponds and mini barrages (4175 ha) that offer enough scope for fisheries development in the region (Baruah 2018). Besides this, the region has a marked elevation gradient variation along its length and breadth, with varied climatic extremes ranging from sub-tropical in the south to temperate and alpine in the north (Baruah et al. 2017). Despite the huge, vast and varied aquatic resources available in different elevation regimes, the region's fish production is skimpy compared to the adjacent and neighbouring states like Assam. The per capita fish availability is meagre

2.19 kg/y, against the national average of 11 kg/y (Baruah 2018). Thus, fish is imported from neighbouring states to meet the requirement. Intrinsically, fishermen communities are in limited numbers. However, fish hunting has existed since times immemorial, with most people being fish eaters. To limit the fish import and augment the fish production capacity of the region, the vast untapped aquatic resources are to be comprehensively explored and utilised for aquaculture activities. Thus, an attempt was made to identify and demarcate the land suitable for rainbow trout farming in the Tawang district of Arunachal Pradesh using the GIS and MCE approach. This is the first attempt to assess the district Tawang, Arunachal Pradesh, for fisheries development using remote sensing and GIS data.

## Materials and methods

### Description of study area

The study area covers the district Tawang, which is situated between 27° 25′ and 27° 45′ N latitude and 91° 42′ and 92° 39′ E longitude in the western part of Arunachal Pradesh, India, having an approximate geographical area of 2364.62 km$^2$ (Fig. 1). The region's climate is warm humid in southern extremes to temperate in the northern extremes with an annual average temperature ranging from - 2.4 to 12.1 °C and rainfall ranging from 41 to 643 inches (https://en.climate-data.org). The topography is dominated by mountainous terrains, which influence the microclimatic variables of the region. The district lies in the elevation zonation range of 1000–6500 m above sea level, having a large number of upland lakes and riverine resources in its catchment, thus, offering enough scope for cold-water fisheries development.

### Data used for the study

Table 1 provides the specifics of the data utilised for the present study. The United States Geological Survey (USGS) provided Landsat 8 (OLI) data to prepare a land use land cover map of the research area to determine the existing land use pattern. USGS also provided Shuttle Radar Topography Mission (SRTM-30 m) satellite data for comprehending the region's elevational topography and slope characteristics. Prior to further analysis, geometric corrections were made to both data sets. The 1:500,000 scale toposheets numbered 78M11, 78M12, 78M13, 78M14, 78M15, 83A1, 83A2, 83A3, 83A4, 83A5, and 83A6 and district and circle boundary shapefiles were acquired from Survey of India (SOI), Dehradun, and were utilised for demarcating district and circle boundaries in addition to geo-referencing. The road network was digitised using the ArcGIS platform's base map; market places, existing fish farms, and fisheries development
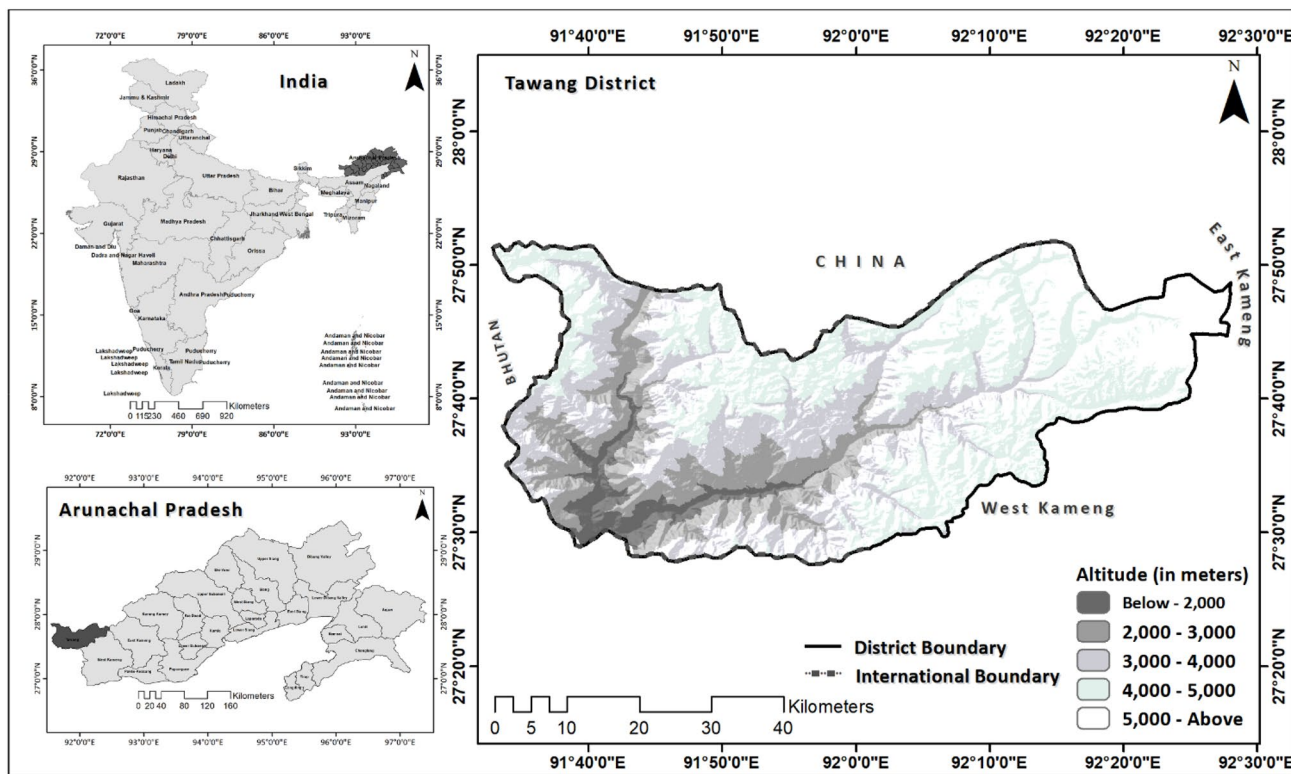
**Fig. 1** Location map of the study area

**Table 1** Details of the data used for the study

| S. No | Data | Specifications | Format | Source |
|---|---|---|---|---|
| 1 | Landsat 8 (OLI) | Path: 137<br>Row: 041<br>Scene Identifier: LC81370412019311LGN00<br>Resolution -30 m | Raster | United States Geological Survey (USGS) https://earth explorer.usgs.gov/ |
| 2 | SRTM DEM | Scene Id: SRTM1N27E091V3; SRTM1N27E092V3<br>Resolution -30 m | Raster | United States Geological Survey (USGS) https://earth explorer.usgs.gov/ |
| 3 | SOI toposheets | Toposheet numbers: 78M11, 78M12, 78M13,<br>78M14, 78M15, 83A1, 83A2, 83A3, 83A4, 83A5,<br>and 83A6<br>Scale: 1: 50,000 | Raster | Survey of India (SOI) https://www.surveyofindia.gov.in/ |

office locations were marked using global positioning system technology (Garmin Oregon, 650). The GIS platform was also used for digitising the accessible water resources in the form of rivers, streams, upland lakes, etc., which were verified using SOI toposheets.

Field sampling was conducted at 35 sites, including lakes, rivers, streams, and existing farms, across several seasons (winter, pre-monsoon, and post-monsoon). Temperature, pH, dissolved oxygen, etc., were measured on-site, whereas alkalinity, ammonia, nitrite, nitrate, hardness, and phosphate were determined using protocols outlined in APHA (2005).

The data on infrastructural facilities, including distance to hatcheries, knowledge of seed supply, and market access, is derived from interviews with line department officials, field visits, and secondary sources. Arc GIS version 10.8 (Environmental Systems Research Institute-ESRI) was used to process the data. The model framework used to locate an area suitable for rainbow trout aquaculture is depicted in Fig. 2. For aquaculture development, forest, urban, glacier, riverine, and road networks were defined as constraining zones. The Arunachal Pradesh Forest Act of 2014 designates certain forest areas as reserved forests; hence, no developmental

**Fig. 2** GIS–MCE modelling framework utilisation for the study

activities are permitted, whereas the other regions are already developed and have no room for expansion.

## Methodology

The criteria or themes appropriate for identifying suitable aquaculture sites were considered based on a thorough literature survey and accounted for based on expert opinions and technical consultations (Mayer and Butler 1993). Based on this, a procedure was set up in the GIS platform, taking into account the attributes of water quality, topography and infrastructural facilities of the study area. A total of Sixteen (16) base/theme layers viz; nine for water quality (water temperature, pH, dissolved oxygen, alkalinity, hardness, ammonia, nitrite, nitrate, and phosphate), three for topography (slope,

elevation and land use land cover) and four for infrastructure facilities (distance to water source, distance to fish hatchery, distance to fish market and accessibility to roads) were prepared. Using kriging interpolation, the theme layers for water quality parameters were generated. The thematic layers for topography were created by classifying slope degree and elevation into several classes, whilst the LULC thematic layer was created using a land use pattern. The infrastructure facilities' thematic layers were created using multiring buffers for all four criteria.

Regarding the efficiency of the specified criterion in site selection, a weight was allocated to it. The ArcGIS 10.8 software (Environmental System Research Institute, USA) was used for the analysis. The analysis results were categorised into three classes viz; most suitable, moderately suitable and

least suitable, based on rainbow trout farming requirements given in Table 2 (FAO 1993).

The theme layers were interpreted and assigned scores based on their suitability rating for use in aquaculture on a scale of 3 to 1, i.e. "3" for most suitable, "2" for moderately suitable and "1" for least suitable (Table 2). The method, applied by many researchers (Nayak et al. 2018; Mohanty et al. 2017; Hossain et al. 2007; Aguilar-Manjarrez et al. 2017; Assefa and Abebe 2018 and Calle Yunis et al. 2020), was also used for our model development with the necessary modifications to the weighting order. The analytical hierarchy process (AHP) and pairwise matrix enabled us to prioritise each criterion to determine how each criterion will be weighted.

## Assigning and determining weights using AHP

This is one of the most important and determining steps of the site selection process. Weightage was assigned to the selected criterion and factors, based on Saaty's (1977) pairwise comparison methodology wherein criteria were weighed against one another to develop a set of relative weights in the context of the analytical hierarchical process (AHP). The relative importance of each criterion was included in the decision model, based on the preferences for fisheries development, concerning the evaluation criteria. The preferences represent a weight given to an evaluation criterion relative to any other criterion. The criteria rating was based on expert opinion and a literature survey (FAO 2002; Hossain et al. 2009; Nayak et al. 2018) in accordance with their relative importance in pairwise comparison (Saaty 1977). A pairwise comparison was conducted at each level of the hierarchy to generate relative weights, called priorities, which differentiated the importance of selected criteria (Saaty 1994). The importance scale ranged from 1 to 9 (Saaty 1977), with 1 indicating factors equally important relative to one another, and 9 indicating one factor to be extremely important compared to another. The values in between reflect different degrees of importance, and the reciprocal values are for inverse comparisons. The eigen values of each factor are calculated through a normalised matrix of comparisons using the AHP algorithm. The principal eigen vector of the

**Table 2** Suitability levels of water quality, infrastructural facilities and topography for rainbow trout farming in eastern Himalayas, Tawang, Arunachal Pradesh, India

| Classification criteria and scale | | | | | |
|---|---|---|---|---|---|
| Parameters | Unit | Most suitable for trout (3) | Moderately suitable for trout (2) | Least suitable for trout (1) | References |
| Water quality | | | | | |
| Water Temp | (ºC) | 9.0–14.5 | 4.5–9.0 and 14.5–18.5 | 3.0—4.5 and 18.5–20 | Francisco et al., (2019) |
| pH | – | 6.6–7.9 | 5.1–6.5 and 8–8.5 | 4.0–5 to 8.6–9.5 | Falconer et al., (2019) |
| DO | (mg/l) | 6.0– 8.5 | 4.5–6.5 and 8.5–9.0 | 3.0–4.5 and 9.0–10.00 | Calle yunis et al., (2020) |
| Total Alkalinity | (mg/l) | 80–180 | 50–180 and 180–230 | 30–50 and 203–280 | Prasad et al., (2014) |
| Hardness | (mg/l) | 60–300 | 40–60 and 300–350 | 20–40 and 350–400 | Aseefa and Abeeba. (2018) |
| Ammonia | (mg/l) | <0.1 | 0.1–0.5 | >0.5 | FAO, (2014) |
| Nitrate | (mg/l) | <0.05 | 0.5–1.0 | >1.0 | Nayak et al, (2018) |
| Nitrite | (mg/l) | <0.01 | 0.01–0.05 | >0.05 | Present Study |
| Phosphate | (mg/l) | <0.25 | 0.25—0.40 | >0.4 | |
| Infrastructural Facilities | | | | | |
| Distance to water source | (m) | <500 | 500–1000 | >1000 | Falconer et al, (2016) |
| Distance to road | (m) | <500 | 500–1000 | 100–1500 | Aseefa and Abeeba 2018; Nayak et al, (2018) |
| Distance to market | (m) | <2000 | 2000–5000 | 5000–10,000 | Present study |
| Distance to hatchery | (km) | <5 | 5–10 | 10–20 | |
| Topography | | | | | |
| Slope | (°) | <5 | 5–15 | 15–25 | Francisco et al., 2019; Falconer et al, (2016) |
| DEM | (m) | 1500–3500 | 1000 – 1500 and 3500–4000 | 500–1000 and 4000–4500 | Calle yunis et al. (2020) |
| Land use Land Cover (LULC) | - | Wasteland | Agriculture Land | Grassland & Forestland | Present study |

**Table 3** Random consistency index

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|----|
| RI | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

pairwise comparison matrix of three sub-models/theme layers generated the best fit for a weight of 1. A matrix of preference values and an eigen vector corresponding to the maximum eigen value were calculated based on the preferences providing a metric for judging the relative importance of criterion attributes (Table 3). The pairwise comparison matrix and normalised pairwise comparison matrix were used to calculate the principal eigen vector and the principal eigen value (λ max) was then calculated from it.

The consistency index was calculated as,

$$CI = \frac{(\lambda_{max-n})}{(n-1)}, \tag{1}$$

where n is the number of criteria.

Then, the consistency ratio was calculated as,

$$CR = \frac{CI}{RI}, \tag{2}$$

where R.I. is the random consistency index.

C.R. indicates the degree of consistency or inconsistency in the decision-making (Eq. 2). Saaty (1980) believed that a C.R. of < 0.1 was acceptable and demonstrated good consistency in judgment, and if C.R. was > 0.1, inconsistencies prevailed, yielding improper results.

Thus, this technique was employed in generating the relative weights for various parameters for rainbow trout farming development in the region. A site suitability rating was performed per parameter with spreadsheet calculations for consistency ratio, as shown in Table 3. The consistency ratios developed for water quality, topography, and infrastructural facilities were 0.012, 0.011 and 0.090, respectively. The C.R. values calculated were well below 0.1, as Saaty (1977) recommended, nullifying the chances of a biased weight allocation to the parameters.

Based on weightage for different parameters from Tables 4, 5 and 6, the suitability maps for water quality, topography and infrastructural facilities were prepared by adding all the criteria and running the formula in the raster calculator of the spatial analyst module of ArcGIS 10.8.

$$Grid_{result} = \sum_{I=1} (grid_i * weight_i) \dots presented\ in$$

Eqs.3–5.

$$
\begin{aligned}
Water\ quality_{grid} = {}& Grid_{temperature} \times 0.26 \\
& + Grid_{DO} \times 0.18 \\
& + Grid_{PH} \times 0.17 \\
& + Grid_{Alkalinity} \times 0.009 \\
& + Grid_{Hardness} \times 0.08 \\
& + Grid_{Ammonia} \times 0.08 \\
& + Grid_{Nitrite} \times 0.06 \\
& + Grid_{Nitrate} \times 0.05 \\
& + Grid_{Phosphate} \times 0.03,
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
Topography_{grid} = {}& Grid_{slope} \times 0.44 + Grid_{Elevation} \times 0.30 \\
& + Grid_{LULC} \times 0.26,
\end{aligned} \tag{4}
$$

$$
\begin{aligned}
Infrastructure\ facilities_{grid} \\
= {}& Grid_{Distance\ to\ water\ source} \times 0.51 \\
& + Grid_{Distance\ to\ Fish\ hatchery} \times 0.23 \\
& + Grid_{Distance\ to\ Roads} \times 0.18 \\
& + Grid_{Distance\ to\ fish\ market} \times 0.08.
\end{aligned} \tag{5}
$$

For final aquaculture site suitability development, these three sub-models, viz., water quality sub-model, topography sub-model and infrastructure facilities sub-model, were subjected to pairwise comparison (Saaty 1977) to generate relative weights of importance (Table 7). Based on the weightage, the final suitability map was generated using Eq. 6, which is given below.

$$
\begin{aligned}
Site\ suitability = {}& Grid_{WaterQuality} \times 0.41 \\
& + Grid_{Topography} \times 0.21 \\
& + Grid_{Infrastructure\ Facilities} \times 0.38
\end{aligned} \tag{6}
$$

## Model validation

A comparison of predicted suitable lands and actual farms was used in the model validation. The results were then verified in the field at 15 selected sites from various land use classes selected through stratified random sampling. The aim was to compare the existing farm locations and performances with those predicted through GIS.

**Table 4** Pairwise comparison matrix for assessing relative importance of water quality parameters for rainbow trout farming development

Water quality

| Criteria | units | Temperature | DO | pH | Alkalinity | Hardness | Ammonia | Nitrite | Nitrate | Phosphate |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | (°C) | 1 | 1 | 3/2 | 3 | 3 | 5 | 5 | 5 | 7 |
| DO | (mg/l) | 1 | 1 | 3/2 | 5/3 | 5/3 | 3 | 3 | 3 | 5 |
| pH | (mg/l) | 2/3 | 2/3 | 1 | 3/2 | 3 | 5/3 | 3 | 5 | 5 |
| Alkalinity | (mg/l) | 1/3 | 3/5 | 2/3 | 1 | 1 | 3/5 | 3/2 | 3/2 | 3 |
| Hardness | (mg/l) | 1/3 | 3/5 | 1/3 | 1 | 1 | 3/2 | 3/2 | 3/2 | 2 |
| Ammonia | (mg/l) | 1/5 | 1/3 | 3/5 | 5/3 | 2/3 | 1 | 7/5 | 5/3 | 3 |
| Nitrite | (mg/l) | 1/5 | 1/3 | 1/3 | 2/3 | 2/3 | 5/7 | 1 | 5/4 | 2 |
| Nitrate | (mg/l) | 1/5 | 1/3 | 1/5 | 2/3 | 3/5 | 3/5 | 4/5 | 1 | 5/3 |
| Phosphate | (mg/l) | 1/7 | 1/5 | 1/5 | 1/3 | 1/2 | 1/3 | 1/2 | 3/5 | 1 |

Normalised matrix

| Criteria | units | Temperature | DO | pH | Alkalinity | Hardness | Ammonia | Nitrite | Nitrate | Phosphate | Sum | Criteria weight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | (°C) | 0.25 | 0.20 | 0.24 | 0.26 | 0.25 | 0.35 | 0.28 | 0.24 | 0.24 | 2.30 | 0.26 |
| DO | (mg/l) | 0.25 | 0.20 | 0.24 | 0.14 | 0.14 | 0.21 | 0.17 | 0.15 | 0.17 | 1.65 | 0.18 |
| pH | (mg/l) | 0.16 | 0.13 | 0.16 | 0.13 | 0.25 | 0.12 | 0.17 | 0.24 | 0.17 | 1.53 | 0.17 |
| Alkalinity | (mg/l) | 0.08 | 0.12 | 0.11 | 0.09 | 0.08 | 0.04 | 0.08 | 0.07 | 0.10 | 0.78 | 0.09 |
| Hardness | (mg/l) | 0.08 | 0.12 | 0.05 | 0.09 | 0.08 | 0.10 | 0.08 | 0.07 | 0.07 | 0.75 | 0.08 |
| Ammonia | (mg/l) | 0.05 | 0.07 | 0.09 | 0.14 | 0.06 | 0.07 | 0.08 | 0.08 | 0.10 | 0.74 | 0.08 |
| Nitrite | (mg/l) | 0.05 | 0.07 | 0.05 | 0.06 | 0.06 | 0.05 | 0.06 | 0.06 | 0.07 | 0.51 | 0.06 |
| Nitrate | (mg/l) | 0.05 | 0.07 | 0.03 | 0.06 | 0.05 | 0.04 | 0.05 | 0.05 | 0.06 | 0.45 | 0.05 |
| Phosphate | (mg/l) | 0.04 | 0.04 | 0.03 | 0.03 | 0.04 | 0.02 | 0.03 | 0.03 | 0.03 | 0.29 | 0.03 |

Consistency ratio (CR)=0.012, Consistency index (CI)=0.018, Random index (RI)=1.45 (N-9)

**Table 5** Pairwise comparison matrix for assessing relative importance of topographic parameters for rainbow trout farming development

Topography

| Criteria | Slope | Elevation | LULC |
|---|---|---|---|
| Slope | 1 | 5/3 | 3/2 |
| Elevation | 3/5 | 1 | 5/4 |
| LULC | 2/3 | 4/5 | 1 |

Normalised matrix

| Criteria | Slope | | Elevation | LULC | Sum | Criteria Weight |
|---|---|---|---|---|---|---|
| Slope | 0.44 | | 0.48 | 0.40 | 1.32 | 0.44 |
| Elevation | 0.26 | | 0.29 | 0.33 | 0.89 | 0.30 |
| LULC | 0.29 | | 0.23 | 0.27 | 0.79 | 0.26 |

Consistency ratio (CR) = 0.011, Consistency index (CI) = 0.006, Random index (RI) = 0.58 (N-3)

*LULC: Land use land cover

# Results

The present study used sixteen (16) parameters/factors to find land suitable for rainbow trout farming under three themes: water quality, topography, and infrastructure facilities. The selected criteria were analysed and corresponding spatial layers/ themes were generated. These themes and layers describe the requirements and constraints that govern site selection, particularly for rainbow trout aquaculture. The selected criteria were assessed pair wise for their relative importance, and relative weights were determined. For a complete analysis, the results of these selected criteria are presented separately in these three sub-models (Table 4, 5, 6, 7).

The water quality parameters recorded were water temperature, pH, dissolved oxygen, total hardness, alkalinity, ammonia, nitrite, nitrate and phosphate. The data of the selected sampling sites and their correlation matrix are given in Tables 8 and 9, respectively. It can be seen that temperature is positively co-related with dissolved oxygen ($r > 0.4496$; $p < 0.001$), pH ($r > 0.549$; $p < 0.0001$), alkalinity ($r > 0.3582$; $p < 0.01$), nitrate ($r > 0.5586$; $p < 0.0001$) and phosphate ($r > 0.2507$; $p <$ not significant) and negatively co-related with hardness ($r = -0.139$; $p =$ not significant), ammonia ($r = -0.538$; $p < 0.0001$), nitrite ($r = -0.193$; $p =$ not significant). Positive co-relation exists between dissolved oxygen and pH ($r = 0.680$; $p < 0.00001$), alkalinity ($r = 0.665$; $p < 0.00001$), hardness ($r = 0.403$; $p < 0.001$), nitrate ($r = 0.385$; $p < 0.01$) and phosphate ($r = 0.014$; $p =$ NS), whereas negative co-relation of dissolved oxygen exists with ammonia ($r = -0.668$; $p < 0.00001$) and nitrite ($r = -0.4418$; $p < 0.001$). pH was positively co-related to alkalinity ($r = 0.859$ $p < 0.00001$), hardness ($r = 0.575$; $p < 0.0001$), nitrate ($r = 0.318$; $p < 0.01$) and phosphate

($r = 0.135$; $p =$ NS) and negatively co-related to ammonia ($r = -0.694$; $p < 0.00001$) and nitrite ($r = -0.235$; $p =$ NS). In addition to pH and DO, hardness was observed to be positively correlated with alkalinity and negatively correlated with other parameters. Alkalinity has demonstrated a similar association pattern. Nitrate was negatively correlated with ammonia, nitrite, and hardness. However, the correlation was not statistically significant. There was a negative correlation between ammonia and every other studied parameter except nitrite, which was similarly non-significant.

Using Kriging interpolation, the appropriate theme layers of all the investigated water quality parameters were generated (Fig. 5) and, based on the rainbow trout farming requirements (Table 2), the suitability layers of each parameter were generated (Fig. 5). The pairwise comparison analysis yielded weightages of 0.26 for temperature, 0.18 for dissolved oxygen 0.17 for pH, 0.09 for alkalinity, 0.08 for hardness and ammonia, 0.06 for nitrite, 0.05 for nitrate and 0.03 for phosphate (Eq. 3) with a consistency index and consistency ratio of 0.018 and 0.012, respectively (Table 3). It was, thus, found that, under the water quality sub-model, water temperature influences the most (26%) in site suitability analysis, followed by dissolved oxygen (18%) and pH (17%). At the same time, criteria such as alkalinity, hardness, ammonia, nitrite, nitrate and phosphate were minimally critical (3–9%) for rainbow trout farming (Table 4). Using the weights generated through pairwise comparison (Eq. 3), a sub-model was run and a water quality suitability map for rainbow trout was generated (Fig. 5). Based on this, the area was categorised into two zones, namely most suitable and moderately suitable for rainbow trout (Fig. 5). The area encompassed under respective suitability zones was 63.42% and 36.58%, respectively (Table 10).

**Table 6** Pairwise comparison matrix for assessing relative importance of infrastructural parameters for rainbow trout farming development

Infrastructural facilities

| Criteria | Distance to water source | Distance to fish hatchery | Distance to road | Distance to fish market |
|---|---|---|---|---|
| Distance to water source | 1 | 3 | 4 | 4 |
| Distance to fish hatchery | 1/3 | 1 | 2 | 3 |
| Distance to road | 1/4 | 1/2 | 1 | 4 |
| Distance to fish market | 1/4 | 1/3 | 1/4 | 1 |

Normalised matrix

| Criteria | Distance to water source | Distance to fish hatchery | Distance to road | Distance to fish market | Sum | Criteria Weight |
|---|---|---|---|---|---|---|
| Distance to water source | 0.55 | 0.62 | 0.55 | 0.33 | 2.05 | 0.51 |
| Distance to fish hatchery | 0.18 | 0.21 | 0.28 | 0.25 | 0.92 | 0.23 |
| Distance to road | 0.14 | 0.10 | 0.14 | 0.33 | 0.71 | 0.18 |
| Distance to fish market | 0.14 | 0.07 | 0.03 | 0.08 | 0.32 | 0.08 |

Consistency ratio (CR) = 0.09, Consistency index (CI) = 0.081, Random index (RI) = 0.90 (N-4)

**Table 7** Pairwise comparison matrix for assessing relative importance of different sub-models for rainbow trout farming development

| Sub-models | | | |
| --- | --- | --- | --- |
| Criteria | Water Quality | Topography | Infrastructure facilities |
| Water Quality | 1 | 3/2 | 3/2 |
| Topography | 2/3 | 1 | 2/5 |
| Infrastructure facilities | 2/3 | 5/2 | 1 |
| Normalised matrix | | | |
| Sub-models | Water Quality | Topography | Infrastructure facilities | SUM | Criteria weight |
| Water Quality | 0.43 | 0.30 | 0.52 | 1.25 | 0.42 |
| Topography | 0.29 | 0.20 | 0.14 | 0.62 | 0.21 |
| Infrastructure facilities | 0.29 | 0.50 | 0.34 | 1.13 | 0.38 |

Consistency ratio (CR) = 0.10, Consistency index (CI) = 0.060, Random index (RI) = 0.58 (N-3)

Under the topography sub-model, the SRTM DEM and Landsat 8 (OLI) satellite data were geo-rectified and atmospherically corrected prior to their further analysis. The SRTM DEM was divided into five distinct elevation classes: below 2000 m, 2000–3000 m, 3000–4000 m, 4000–5000 m and above 5000 m. Figure 6 depicts the preparation of the suitable layer according to Table 2's criteria. Likewise, four distinct slope classes, namely 0–5°, 5–15°, 15–25° and above 25°, were derived from SRTM DEM, and corresponding suitability layers were generated (Fig. 6). Following supervised classification, a map of the study area's land use and land cover (LULC) was created using Landsat 8 (OLI) data. In the study region, A total of 8 land use classes were identified, namely, agricultural land, built-up, forest, grassland and grazing land, shifting cultivation, snow/glacier area, wastelands and waterbodies (Fig. 3). The suitability layers were generated according to Table 2 as shown in Fig. 6. The pairwise comparison produced weightings of 0.44 for slope, 0.30 for elevation and 0.26 for land use pattern (Eq. 4) with a consistency index and consistency ratio of 0.006 and 0.011 respectively (Table 5). Under the topography sub-model, slope influences rainbow trout farming the most (44%), followed by elevation (30%) and land use land cover pattern (26%) (Table 5). The weights derived were used (Eq. 4) to estimate the topography sub-model's suitability. The study region was categorised into three zones, namely most suitable, moderately suitable and least suitable for rainbow trout, based on the topography sub-model (Fig. 6). The areas covered under each suitability class were 0.40%, 33.84% and 64.77%, respectively (Table 10).

Under the sub-model for infrastructure facilities, four criteria were considered: distance to the water source, distance to the fish hatchery, distance to the road, and distance to the fish market. The water sources, including riverine and lacustrine resources, were defined using Landsat 8 (OLI) data and ARCGIS hydrology tools (Figs. 4, 7). The road network of the study area was manually digitised from the GIS platform's existing base map (Fig. 7). The positions of the fish market and fish hatchery were marked using a handheld GPS (Garmin Oregon, 650) and secondary data. Multiring buffers were utilised to prepare the theme layers for all four criteria. A multiring buffer of 500 m, 500–1000 m, and 1000–1500 m was developed for the distance to the water source layer (Fig. 7). Similarly, a multiring buffer of 0.5 km, 0.5–1 km, and 1–1.5 km was built for distance to the road (Fig. 7). For the distance to the fish market, a buffer of 2 km, 2–5 km, and 5–10 km was established (Fig. 7). Lastly, for the distance to the fish hatchery, a buffer of 5 km, 5–10 km, and 10–20 km was built (Fig. 7). Figure 7 depicts the suitability layers of all the criteria prepared according to Table 2. The pairwise comparison resulted in a weighting of 0.51 for the distance to the water source, 0.23 for the distance to the fish hatchery, 0.18 for the distance to the road, and 0.08 for

**Table 8** Water quality parameters of the selected sampling stations of district Tawang, Arunachal Pradesh

| S.NO | Sampling site | Temperature (°c) | Dissolved Oxygen (mg/l) | PH | Alkalinity (mg/l) | Hardness (mg/l) | Ammonia (mg/l) | Nitrite (mg/l) | Nitrate (mg/l) | Phosphate (mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | River | 8.1 ± 0.12 | 8.2 ± 0.95 | 7.82 ± 0.95 | 190 ± 2.95 | 181 ± 5.35 | 0.01 ± 0.001 | 0.01 ± 0.005 | 0.01 ± 0.001 | 0.06 ± 0.005 |
| 2 | River | 8.2 ± 0.55 | 8.15 ± 0.85 | 7.27 ± 0.35 | 160 ± 5.35 | 152 ± 3.35 | 0.01 ± 0.008 | 0.01 ± 0.005 | 0.02 ± 0.008 | 0.05 ± 0.002 |
| 3 | River | 15 ± 0.35 | 8.3 ± 0.18 | 7.93 ± 0.85 | 172 ± 4.96 | 167 ± 2.95 | 0.01 ± 0.001 | 0.01 ± 0.003 | 0.01 ± 0.006 | 0.06 ± 0.005 |
| 4 | River | 11.25 ± 0.25 | 8.08 ± 0.68 | 8.02 ± 1.75 | 177 ± 4.35 | 170 ± 5.74 | 0.02 ± 0.009 | 0.02 ± 0.003 | 0.01 ± 0.001 | 0.07 ± 0.009 |
| 5 | Trout farm | 6.07 ± 0.75 | 8.16 ± 1.15 | 8.05 ± 0.68 | 175 ± 5.74 | 170 ± 3.75 | 0.02 ± 0.001 | 0.01 ± 0.003 | 0.02 ± 0.005 | 0.06 ± 0.001 |
| 6 | Upland lake | 6.8 ± 0.12 | 6.86 ± 1.75 | 6.37 ± 0.18 | 142 ± 3.35 | 138 ± 3.35 | 0.01 ± 0.006 | 0.02 ± 0.003 | 0.03 ± 0.006 | 0.05 ± 0.007 |
| 7 | Upland lake | 7.37 ± 1.75 | 6.79 ± 0.65 | 7.35 ± 0.74 | 150 ± 3.75 | 147 ± 2.95 | 0.02 ± 0.001 | 0.02 ± 0.006 | 0.02 ± 0.007 | 0.06 ± 0.002 |
| 8 | Stream | 5.02 ± 0.65 | 8.17 ± 1.34 | 7.04 ± 1.36 | 164 ± 7.70 | 161 ± 8.25 | 0.02 ± 0.004 | 0.01 ± 0.002 | 0.01 ± 0.001 | 0.05 ± 0.005 |
| 9 | Upland lake | 7.88 ± 0.65 | 7.25 ± 0.18 | 5.14 ± 0.86 | 38 ± 1.25 | 36 ± 5.35 | 0.03 ± 0.004 | 0.010.003 | 0.05 ± 0.006 | 0.07 ± 0.005 |
| 10 | Upland lake | 5.21 ± 0.12 | 6.98 ± 0.74 | 5.91 ± 0.65 | 42 ± 1.35 | 39 ± 1.95 | 0.050.005 | 0.01 ± 0.001 | 0.03 ± 0.007 | 0.05 ± 0.006 |
| 11 | Upland lake | 6.32 ± 0.85 | 7.12 ± 1.54 | 5.440.74 | 36 ± 3.25 | 34 ± 1.35 | 0.05 ± 0.008 | 0.01 ± 0.001 | 0.04 ± 0.002 | 0.05 ± 0.003 |
| 12 | Upland lake | 8.17 ± 0.95 | 6.77 ± 1.34 | 7.23 ± 0.95 | 155 ± 2.95 | 149 ± 8.25 | 0.05 ± 0.003 | 0.02 ± 0.009 | 0.05 ± 0.006 | 0.05 ± 0.009 |
| 13 | Stream | 5.13 ± 0.12 | 8.06 ± 1.15 | 7.1 ± 1.36 | 172 ± 8.38 | 169 ± 5.74 | 0.01 ± 0.001 | 0.01 ± 0.007 | 0.04 ± 0.001 | 0.05 ± 0.005 |
| 14 | Upland lake | 4.07 ± 0.18 | 6.12 ± 3.75 | 5.04 ± 0.68 | 24 ± 1.15 | 22 ± 2.05 | 0.05 ± 0.007 | 0.02 ± 0.003 | 0.03 ± 0.001 | 0.05 ± 0.006 |
| 15 | Stream | 5.32 ± 0.35 | 8.11 ± 1.54 | 6.98 ± 0.95 | 140 ± 4.35 | 133 ± 4.35 | 0.03 ± 0.008 | 0.02 ± 0.007 | 0.06 ± 0.004 | 0.06 ± 0.004 |
| 16 | Upland lake | 9.67 ± 0.68 | 6.43 ± 0.86 | 5.55 ± 0.86 | 75 ± 4.25 | 72 ± 0.95 | 0.05 ± 0.006 | 0.02 ± 0.003 | 0.07 ± 0.003 | 0.07 ± 0.005 |
| 17 | River | 13.5 ± 1.25 | 7.6 ± 0.96 | 7.3 ± 0.35 | 140 ± 3.75 | 85 ± 0.25 | 0.01 ± 0.006 | 0.01 ± 0.003 | 0.01 ± 0.001 | 0.06 ± 0.008 |
| 18 | River | 14.2 ± 1.15 | 7.8 ± 2.94 | 7.6 ± 1.16 | 140 ± 5.25 | 80 ± 1.60 | 0.01 ± 0.004 | 0.01 ± 0.007 | 0.1 ± 0.005 | 0.1 ± 0.009 |
| 19 | River | 15 ± 1.28 | 7.6 ± 0.96 | 7.8 ± 0.95 | 160 ± 1.35 | 80 ± 2.15 | 0.01 ± 0.001 | 0.01 ± 0.003 | 0.54 ± 0.01 | 0.10.003 |
| 20 | River | 14.4 ± 1.15 | 8 ± 0.95 | 7.2 ± 0.66 | 155 ± 0.25 | 80 ± 1.45 | 0.01 ± 0.004 | 0.02 ± 0.001 | 0.5 ± 0.05 | 0.1 ± 0.002 |
| 21 | Stream | 12 ± 1.25 | 8.2 ± 0.65 | 7 ± 0.44 | 135 ± 3.75 | 110 ± 5.35 | 0.02 ± 0.003 | 0.02 ± 0.005 | 0.5 ± 0.05 | 0.04 ± 0.004 |
| 22 | River | 13.5 ± 0.35 | 7.8 ± 1.34 | 7.6 ± 0.76 | 140 ± 8.25 | 90 ± 0.39 | 0.01 ± 0.005 | 0.01 ± 0.002 | 0.04 ± 0.001 | 0.08 ± 0.002 |
| 23 | River | 13.2 ± 1.28 | 8.4 ± 1.16 | 8 ± 0.96 | 135 ± 7.70 | 88 ± 1.47 | 0.02 ± 0.004 | 0.01 ± 0.003 | 0.4 ± 0.02 | 0.08 ± 0.005 |
| 24 | River | 12.8 ± 1.34 | 8.6 ± 1.46 | 8.2 ± 1.25 | 150 ± 5.35 | 95 ± 2.64 | 0.01 ± 0.001 | 0.01 ± 0.004 | 0.3 ± 0.09 | 0.05 ± 0.008 |
| 25 | River | 13.2 ± 0.35 | 8 ± 0.46 | 7.4 ± 0.44 | 140 ± 3.95 | 90 ± 2.15 | 0.01 ± 0.003 | 0.01 ± 0.001 | 0.05 ± 0.007 | 0.05 ± 0.003 |
| 26 | Stream | 13 ± 0.44 | 8.2 ± 1.75 | 7.2 ± 1.36 | 135 ± 1.10 | 95 ± 1.25 | 0.01 ± 0.005 | 0.02 ± 0.003 | 0.4 ± 0.02 | 0.08 ± 0.002 |
| 27 | River | 13 ± 2.14 | 8 ± 0.75 | 7.2 ± 1.16 | 135 ± 5.25 | 95 ± 3.75 | 0.02 ± 0.006 | 0.01 ± 0.002 | 0.5 ± 0.07 | 0.06 ± 0.007 |
| 28 | Stream | 12.6 ± 1.25 | 8.6 ± 2.94 | 7.4 ± 0.74 | 160 ± 5.74 | 105 ± 4.35 | 0.03 ± 0.007 | 0.01 ± 0.002 | 0.52 ± 0.007 | 0.08 ± 0.007 |
| 29 | River | 13 ± 2.14 | 7.8 ± 1.54 | 7.6 ± 0.96 | 155 ± 3.75 | 100 ± 2.85 | 0.01 ± 0.001 | 0.02 ± 0.001 | 0.2 ± 0.07 | 0.5 ± 0.01 |
| 30 | Stream | 12 ± 1.15 | 8.4 ± 0.95 | 7.2 ± 1.96 | 155 ± 1.25 | 110 ± 0.85 | 0.01 ± 0.005 | 0.01 ± 0.002 | 0.3 ± 0.09 | 0.05 ± 0.003 |
| 31 | River | 11.4 ± 0.55 | 8.8 ± 1.15 | 6.8 ± 0.86 | 165 ± 4.20 | 120 ± 8.75 | 0.01 ± 0.001 | 0.01 ± 0.009 | 0.05 ± 0.002 | 0.06 ± 0.006 |
| 32 | River | 14 ± 0.44 | 7.6 ± 1.34 | 7.4 ± 0.96 | 130 ± 2.25 | 85 ± 0.78 | 0.02 ± 0.001 | 0.01 ± 0.001 | 0.12 ± 0.02 | 0.1 ± 0.001 |
| 33 | Stream | 12.6 ± 0.25 | 8.2 ± 0.85 | 8 ± 0.86 | 150 ± 5.35 | 100 ± 1.65 | 0.01 ± 0.006 | 0.01 ± 0.005 | 0.56 ± 0.09 | 0.05 ± 0.001 |
| 34 | Stream | 12 ± 1.28 | 8.2 ± 1.15 | 8 ± 0.85 | 150 ± 5.28 | 110 ± 5.74 | 0.01 ± 0.001 | 0.01 ± 0.008 | 0.41 ± 0.07 | 0.05 ± 0.001 |
| 35 | River | 13.2 ± 0.55 | 8 ± 0.25 | 7.2 ± 2.95 | 140 ± 3.39 | 90 ± 7.70 | 0.02 ± 0.006 | 0.01 ± 0.001 | 0.23 ± 0.04 | 0.1 ± 0.001 |

(* Values are represented as mean and standard deviation)

the distance to the fish market (Eq. 5) with a consistency index and consistency ratio of 0.081and 0.09, respectively (Table 6). Under the infrastructural facilities sub-model, it was discovered that distance to the water source (51%) had the most significant impact, followed by distance to fish hatchery or seed supply (23%), distance to road accessibility (18%), and distance to the fish market (8%) in that order of preponderance (Table 6). The derived weights (Eq. 5) were used in estimating the rainbow trout suitability zones. The sub-model categorised the region into three suitability zones

viz., most, moderate and least suitable zones (Fig. 7) with 1.5%, 6.25% and 1.34% areas under each zone, respectively (Table 10).

Water is the most vital requirement for initiating and sustaining any aquaculture operation, especially in rainbow trout farming, where the availability of pristine cold-water is the first and foremost requirement. Similarly, the fish seed is a critical component of rainbow trout farming. Its availability at the right time is vital for successful fish production, especially in hilly regions where zigzag roads hamper

**Table 9** Pearson correlation matrix of the selected water quality parameters of the District Tawang, Arunachal Pradesh

| Parameter | Temp | DO | PH | Alkalinity | Hardness | Ammonia | Nitrite | Nitrate | Phosphate |
|---|---|---|---|---|---|---|---|---|---|
| Temp | 1 | | | | | | | | |
| DO | 0.45** | 1.00 | | | | | | | |
| PH | 0.55*** | 0.68**** | 1.00 | | | | | | |
| Alkalinity | 0.36* | 0.67**** | 0.86**** | 1.00 | | | | | |
| Hardness | − 0.14 | 0.40** | 0.58*** | 0.82**** | 1.00 | | | | |
| Ammonia | − 0.54*** | − 0.67**** | − 0.69**** | − 0.73**** | -0.41** | 1.00 | | | |
| Nitrite | − 0.46 | − 0.47** | − 0.31 | − 0.17 | 0.18 | 0.48 | 1.00 | | |
| Nitrate | 0.56*** | 0.39* | 0.32* | 0.16 | − 0.23 | − 0.24 | − 0.36 | 1.00 | |
| Phosphate | 0.25 | 0.01 | 0.14 | 0.10 | − 0.09 | − 0.16 | − 0.36 | 0.08 | 1.00 |

Notes: Indicates significant correlation at (*= p < 0.01; ** = p < 0.001; *** p < 0.0001; **** p < 0.00001) levels

transportation, delaying the service and hindering aquaculture operations.

Based on these three sub-models, the final site suitability map was developed by assigning relative importance in terms of weights to each sub-model, generated through pairwise comparison (Eq. 6; Table 7). In this case, all constraint layers, such as forests, built-up areas, glaciers, rivers, and roads, were masked because such areas could not support development activities. The corresponding weights generated were 0.41 for the water quality sub-model, 0.21 for the topography sub-model and 0.38 for the infrastructural facilities sub-model. Thus, under the final suitability model, it was found that water quality (41%) was the most significant factor influencing site selection, followed by infrastructure (38%) and topography (21%) (Table 7). The final site suitability map for rainbow trout farming is shown in Fig. 8. We found out that, out of the total geographic area (235,757.41 ha) of district Tawang, Arunachal Pradesh, 340.21 ha (0.14%) was most suitable, 1810.98 ha (0.77%) was moderately suitable, and 50.70 ha (0.02%) was least suitable for trout farming development (Table 11). The constraint areas account for about 99.07% (Fig. 9). The model validation revealed that about 60% of the existing fish farms were present in the suitable category zonation, as revealed through GIS analysis, and 40% in the moderate to least suitable zones.

## Discussion

The study area, Tawang, Arunachal Pradesh, falls in the eastern Himalayan belt at an elevation of above 1000 m above mean sea level. The study mainly focused on identifying suitable areas for rainbow trout farming development. Different criteria were grouped into three sub-models based on water quality, topography, and infrastructural facilities to generate a final output map showing the suitable areas for rainbow trout farming. In these kinds of studies, the accuracy of the results depends directly on the quality of input data, so accurate and updated thematic information is necessary. The developed model identified the best possible aquaculture sites for rainbow trout fish farming within the district of Tawang, Arunachal Pradesh, India. Even a modest increase in rainbow trout production will benefit the region's people in terms of nutrition and employment, as the hilly region has natural limitations to food production capacities and job opportunities.

It is essential for policy makers and implementing agencies to prioritise the implementation of the rainbow trout farming development plan for this region in an industry-enabling futuristic approach by adhering to the ecosystem approach to aquaculture (Aguilar-Manjarrez et al. 2017) along with the essence of ecological, socio-economic and industrial point of views (Dapueto et al. 2015). In such scenarios, where a sector has yet to make its presence felt, a model for assessing potential sites based on multiple criteria would greatly help policymakers monitor and govern the aquaculture venture since its inception.

Researchers have found that when a suitability analysis is performed, a minimal difference in the weighted coefficients can significantly impact the results (Radiarta et al. 2008). Due to this, we have determined the weights by thinking logically, debating scientifically and applying our acquired experiences and expertise on different parameters while judging the various criteria. In most cases, the weights and scores given to the factors were not unanimously agreed upon (Falconer et al. 2016). Thus, onsite feasibility was taken into account while finalising the weighing system. In future, the situation may change based on stakeholder priorities and logistical developments. Bagdanaviciute et al. (2015) found that weights for sub-factors and criteria were often subjective. Our sub-factors were consistent in scores and weighting's, and there were minor deviations in the consistency of our sub-models. This was

**Table 10** Area and percentage under sub-models of different suitability classes of rainbow trout farming in Tawang, Arunachal Pradesh

| Suitability class | Most suitable for trout | | Moderately suitable for trout | | Least suitable for trout | |
|---|---|---|---|---|---|---|
| | (ha) | % | (ha) | % | (ha) | % |
| Water Quality | 150,000.41 | 63.42 | 86,630.91 | 36.58 | – | – |
| Infrastructure Facilities | 3550.93 | 1.5 | 14,745.78 | 6.25 | 3151.72 | 1.34 |
| Topography | 939.49 | 0.40 | 79,786.85 | 33.84 | 152,691.70 | 64.77 |

**Fig. 3** Land use land cover map of the study area
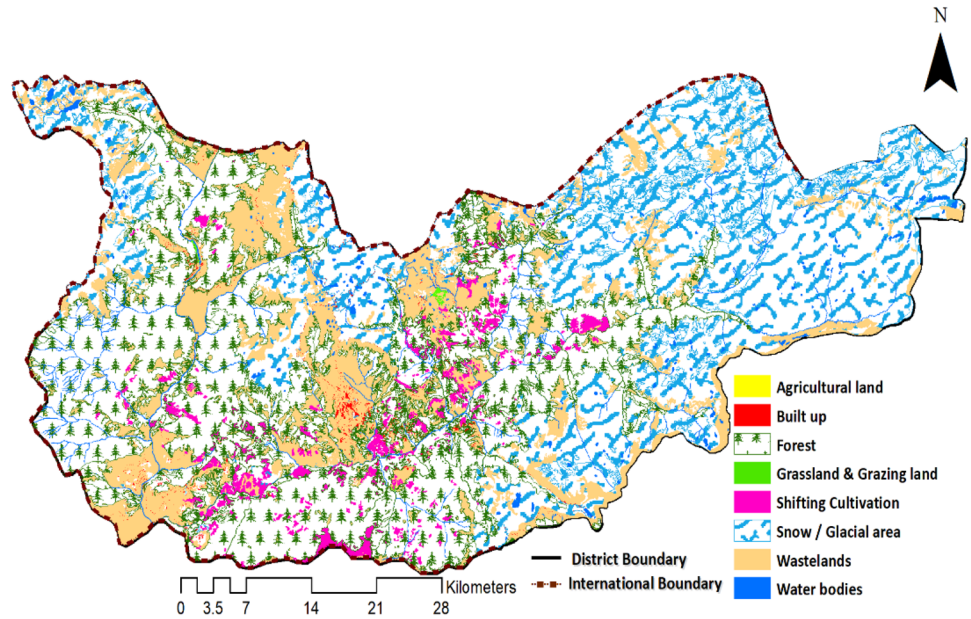


**Fig. 4** Riverine and upland lake resources of the study area
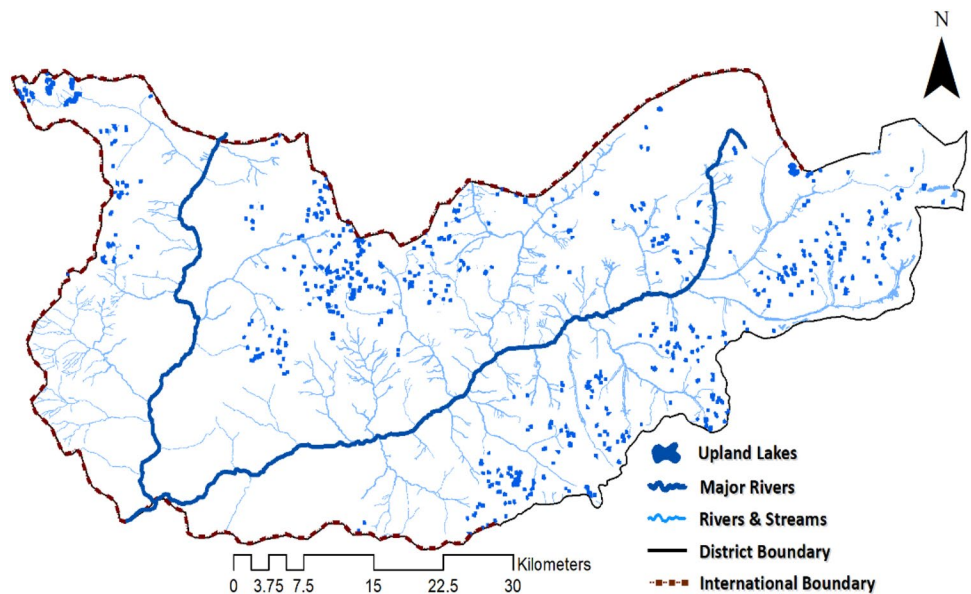


possible due to the familiarity with the location, extensive understanding of rainbow trout farming, and decision-making experience.

It has been realised that the MCE model helps to highlight both the advantages and challenges associated with the endeavour. The major positive factor for the region was its

**Fig. 5** Final water quality suitablity sub-model
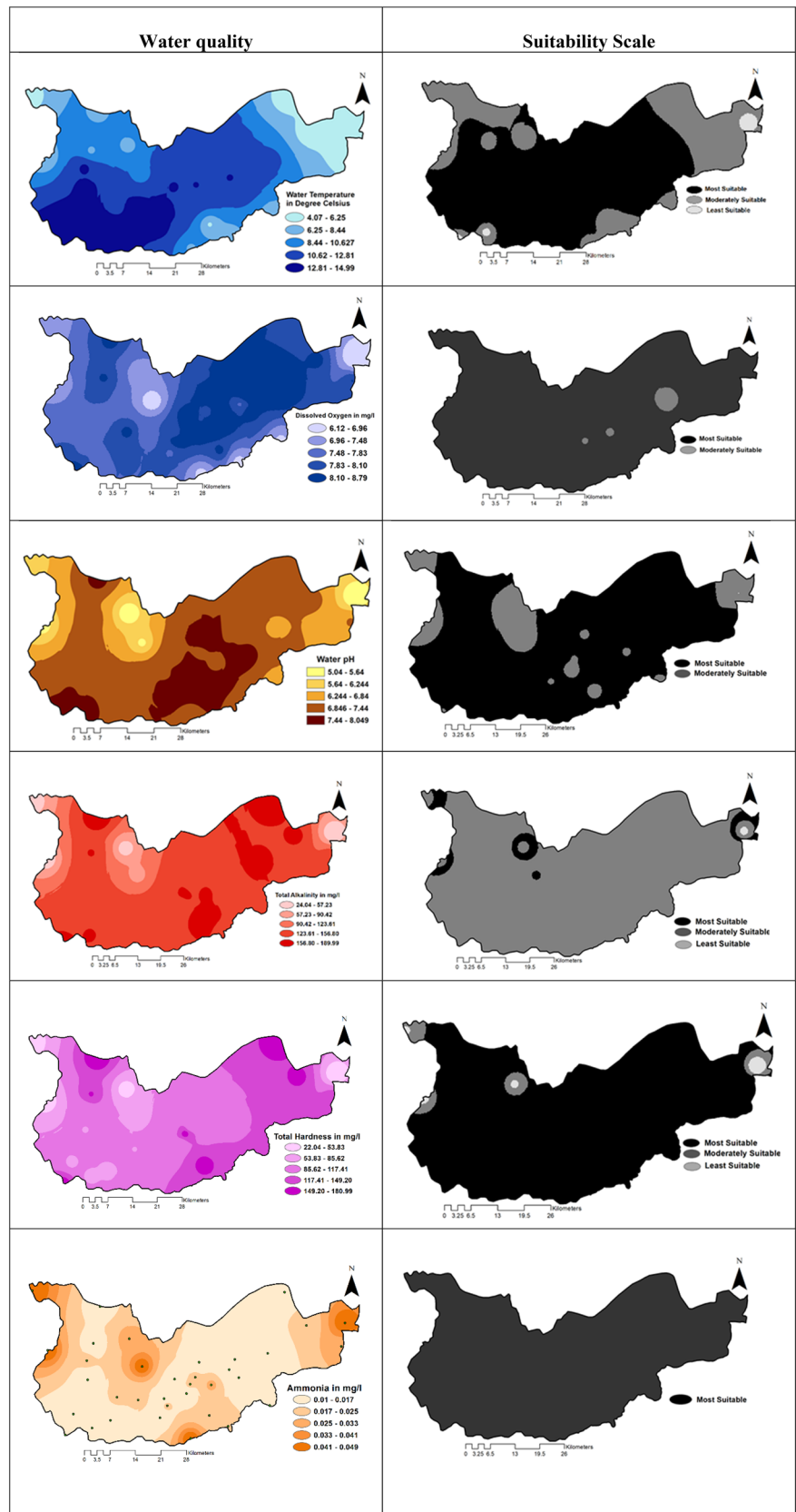
**Fig. 5** (continued)
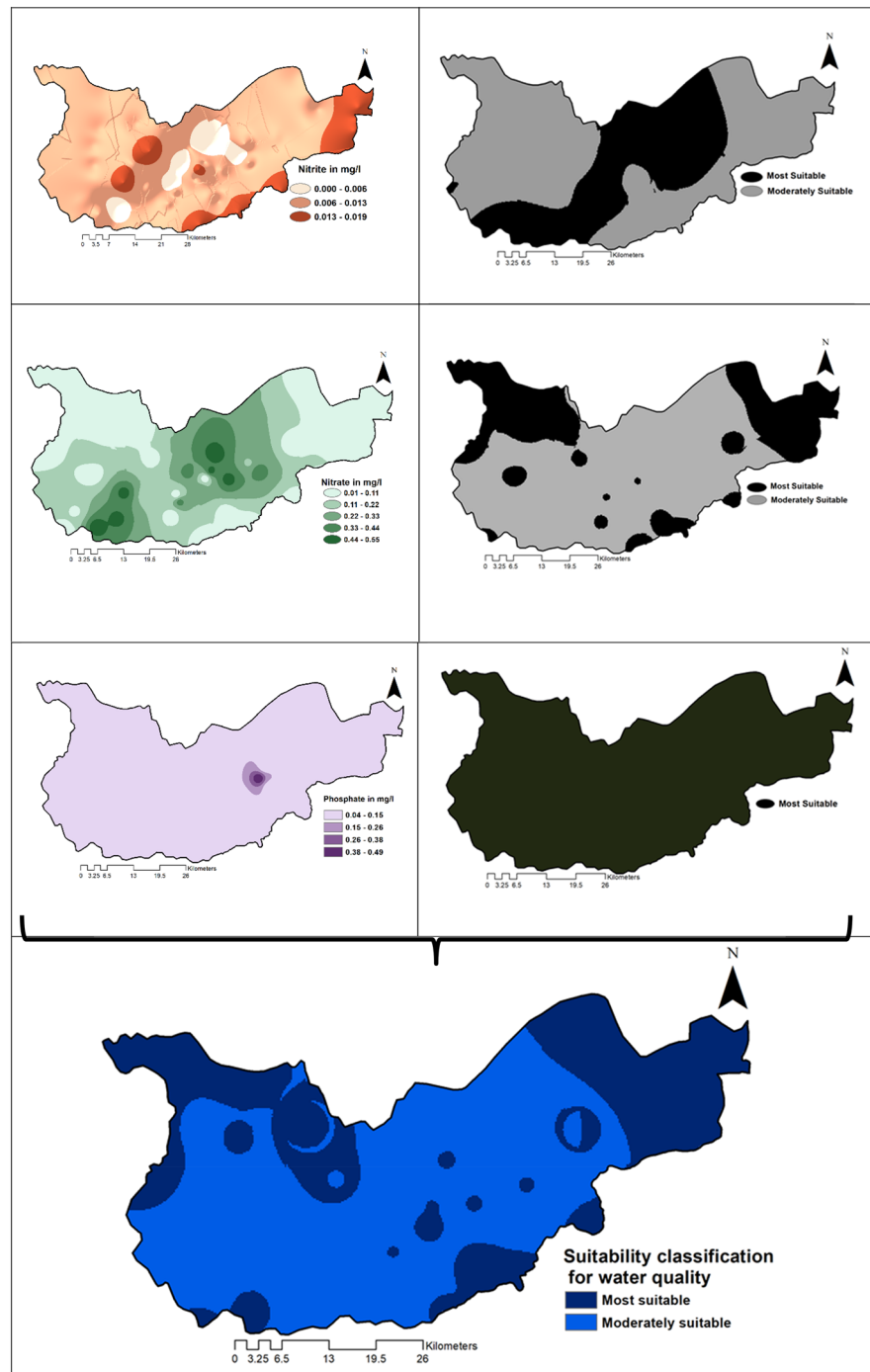


suitable elevation and water temperature. The elevation of the region (3000 m) and the water temperature (< 20 °C) offered a promising environment for initiating and propagating rainbow trout farming. However, the major challenge was the slope (> 25 ) and the accessibility, which seemed to be a major hindrance in this endeavour.

The water quality sub-model (Table 4, Fig. 5) mainly focussed on water temperature, pH, dissolved oxygen and other parameters of aquaculture importance. Table 8 shows

the water quality parameters of the selected sampling stations of the district Tawang, Arunachal Pradesh. In terms of spatial conditions, the recorded water quality variables like water temperature, pH, dissolved oxygen, total hardness, alkalinity, ammonia, nitrite, nitrate, phosphate, etc. were well within the acceptable limits for the culture of rainbow trout (Dunning and Sloan 2001; Hinshaw, 2000; Cain and Garling. 1993; Piper et al. 1982; Klontz. 1991; FAO 2011c; Bhagat and Barat 2015).

**Fig. 6** Final topography suit-
ablity sub-model
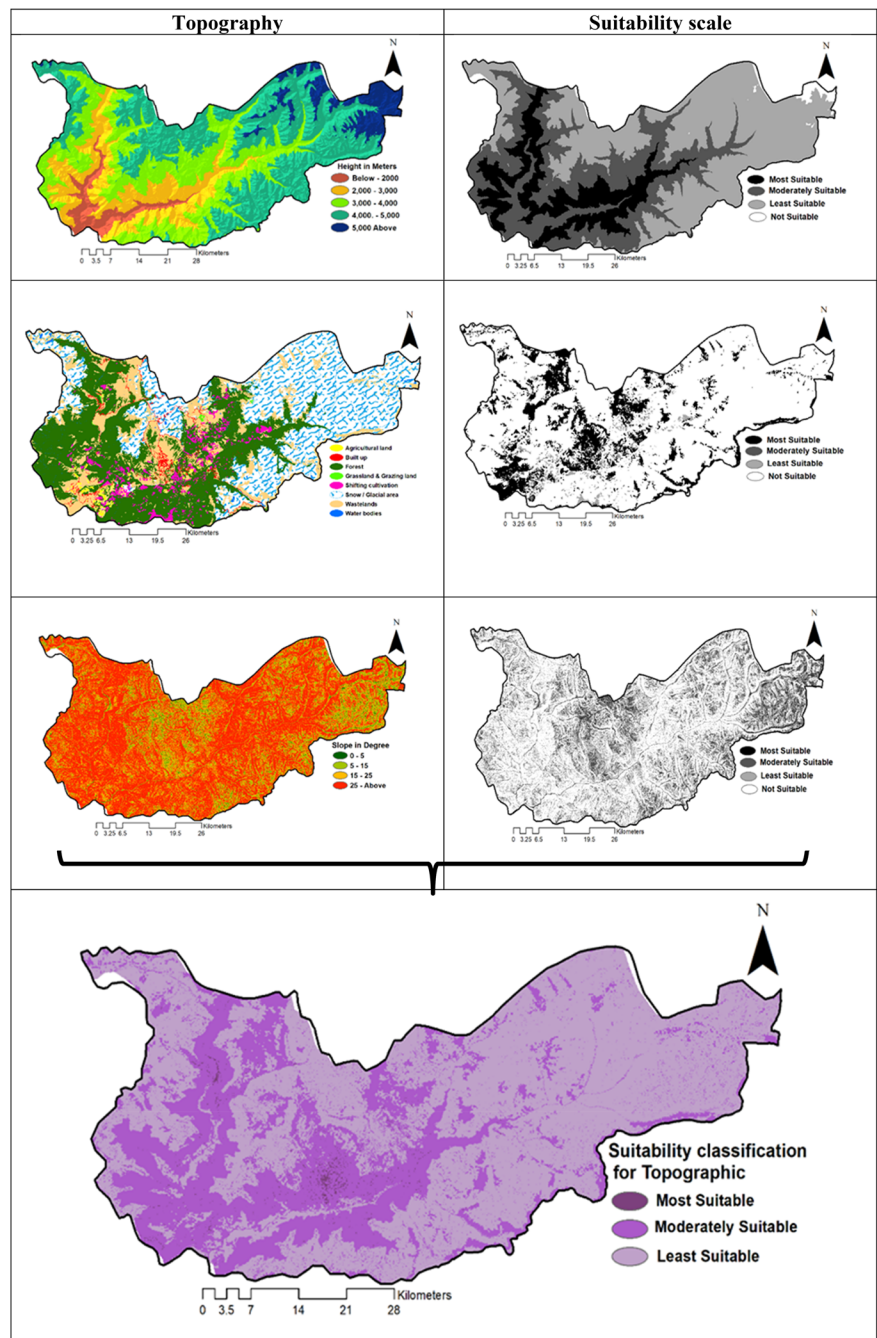


Water temperature is a critical factor in aquaculture, but it is often beyond human control. It depends on factors such as the quantity of sunlight reaching the water, the ambient air temperature, or the water's temperature as it flows through the culture unit (MacIntyre et al. 2008). The temperature at which an organism lives and develops is crucial to its success. Trout, like other aquaculture animals, are poikilothermic. Therefore, water temperature is most crucial to their development and survival. The trout is typically associated with cold-water production facilities, despite a wide range of temperatures being suitable for its growth. The ideal temperature range for rainbow trout seed production is between 9 and 13 °C (Francisco et al. 2019). Although temperatures up to 4$^O$ and 18 $^O$C are conducive to feed consumption, the growth performance is hampered, and temperatures below 4° and above 20 °C are considered detrimental to its growth (Francisco et al. 2019; Calle Yunis et al. 2020). The temperature of the study area was recorded in the range of 4.04–14.4 °C (Table 8) and was, therefore, deemed suitable for rainbow trout aquaculture. This is in accordance with the suggested temperature ranges as proposed by (Summerfelt

**Fig. 7** Final infrastructural faciltites suitablity sub-model
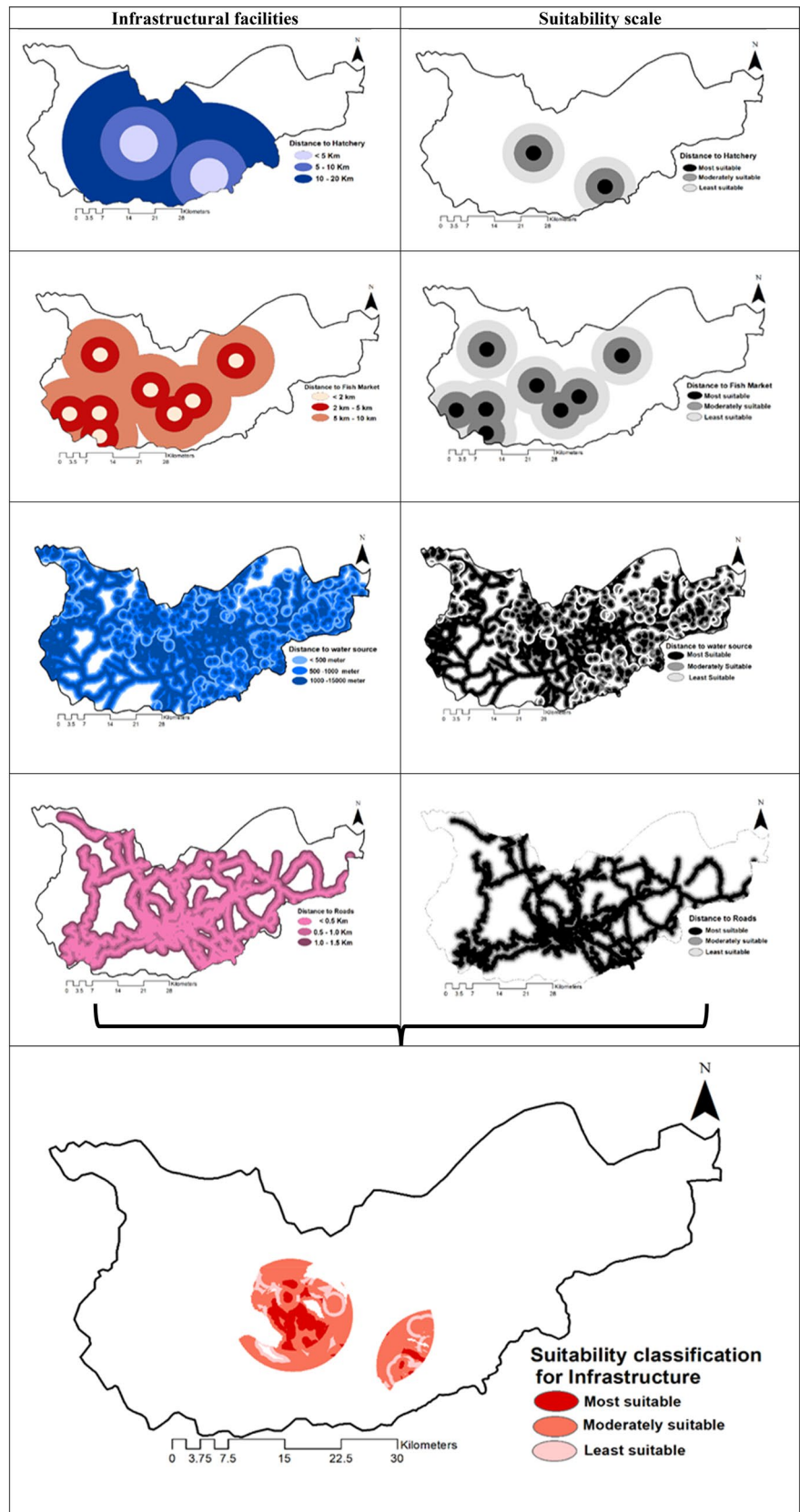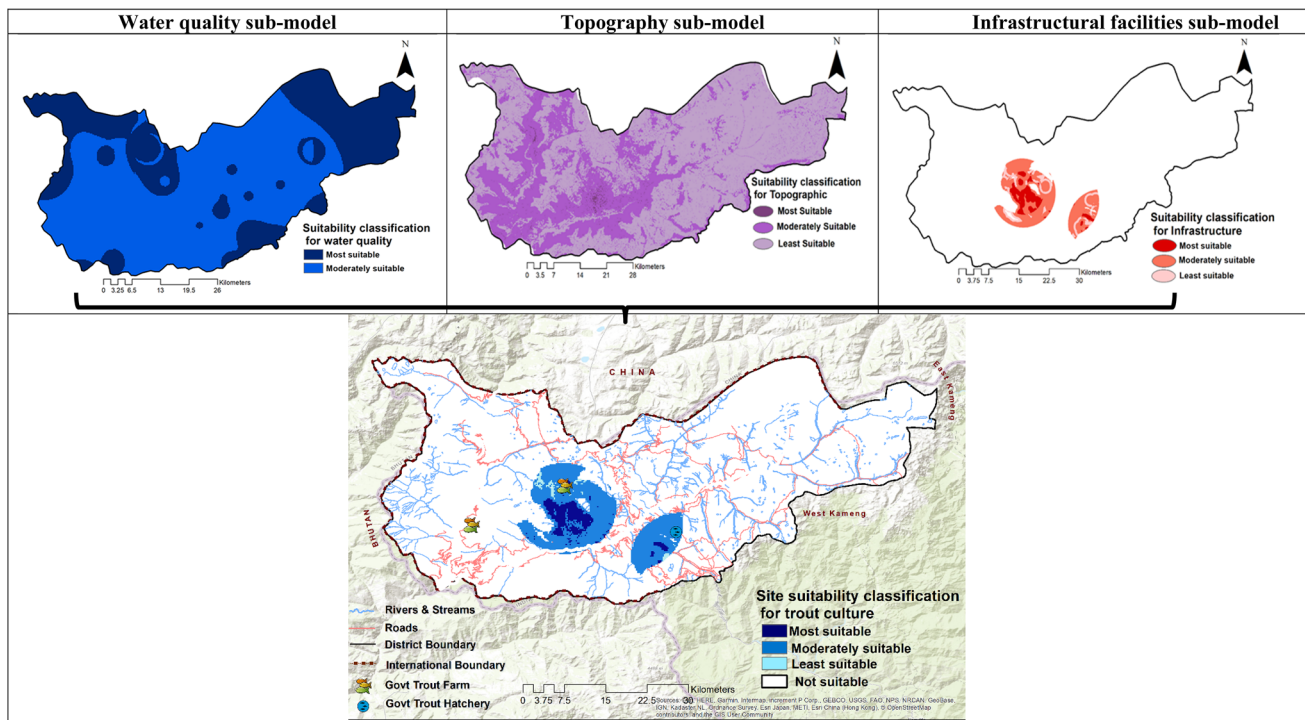
**Fig. 8** Final site suitability map of the study area

**Table 11** Final area under different suitability classes of rainbow trout farming in Tawang, Arunachal Pradesh

| S. No | Suitability class | Area (ha) | Percentage (%) |
|---|---|---|---|
| 1 | Most suitable for trout | 340.21 | 0.14 |
| 2 | Moderately suitable for trout | 1810.98 | 0.77 |
| 3 | Least suitable for trout | 50.70 | 0.02 |
| 4 | Constraints (forest, Glacier, lakes, streams, rivers, Built Up and roads etc.) | 215,043.74 | 99.07 |
| | Total (ha) | 235,757.41 | 100 |

2000; Boyd and Tucker 1998; Woynarovich et al. 2011). Summerfelt (2000) stated that the normal ambient temperature for rainbow trout is 15 ℃., whereas Boyd and Tucker (1998) believed that rainbow trout grow the best in a temperature range of 10–16 °C. Woynarovich et al. (2011) consider a temperature of 16–18 °C optimum for the growth of rainbow trout.

Another significant and vital indicator of water quality is the concentration of dissolved oxygen (DO), which directly impacts aquatic organisms' ability to consume food and regulate their metabolism, as well as indirect effects on the water's overall quality. Salmonids have greater oxygen requirements in the water. Fish start to exhibit signs of choking if the concentration falls below 3 mg/l (Svobodova et al. 1993). To be deemed safe for rainbow trout, a minimum DO of 5–6 mg/l is recommended (Smart 1981; Colt and

Tomasso 2001). The study area's measured dissolved oxygen levels were ideal for raising rainbow trout (Table 8). Even with dissolved oxygen, a fundamental parameter, there is debate over the ideal minimum level for rainbow trout culture, with suggestions ranging from 5 to 9 mg/l depending on temperature. The study areas DO levels were higher than the generalised limit for cold-water fish culture.

Additionally, oxygen is needed to keep fish and bacteria that break down fish-producing waste healthy and to fulfil the oxygen needs of the culture itself. There is widespread agreement that fish thrive in environments where oxygen levels are close to, or even above, saturation. This results in greater growth, a lower feed conversion ratio, and more overall production (MacIntyre et al. 2008). Jobling (1995) pointed out that trout start to lose their appetite when the oxygen level drops below 60%. According to a study by Levy et al. (1989), salmonids exhibit a behavioural avoidance of low oxygen levels. Additionally, it has been observed that the distribution of fish shifts, with fish going towards the surface or water inlet, where DO concentrations are higher (Wedemeyer 1996).

The water's pH is critically important in fish farming because of the profound effects it has on fish metabolism and physiology. Water in aquaculture systems should have a pH between 7.5 and 8.5 (Boyd and Tucker 1998). Outside that range, there is a higher risk of stress, increased susceptibility to sickness, decreased output, stunted growth, and even mortality. When acidic or basic compounds, such

**Fig. 9** Constraint layers of the study area
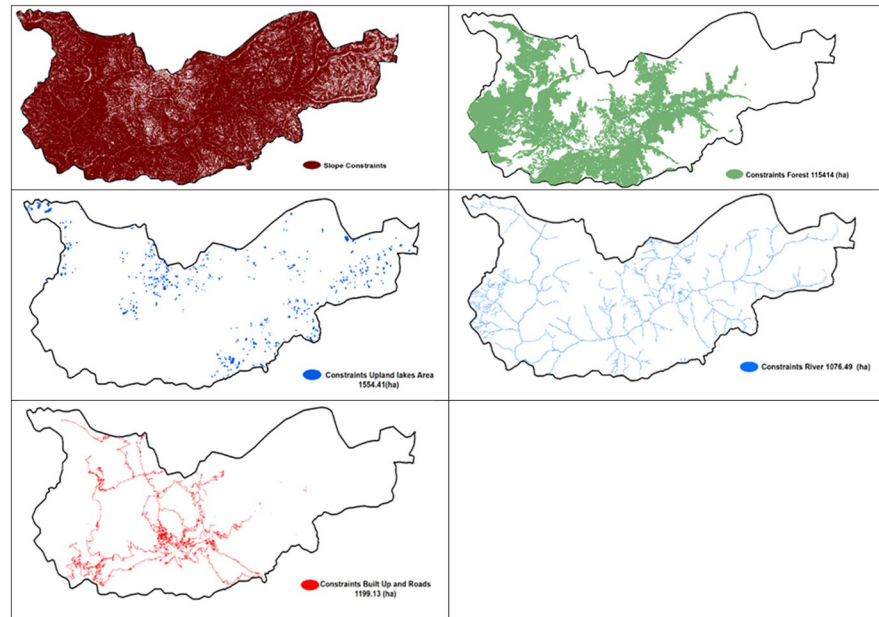


as mineral acids and hydroxides, are discharged or precipitated into the water, the water's pH changes (Wagner et al. 1997). Tissue damage and bleeding in the gills and the lower body are common reactions to pH values that are too high or too low for a fish's tissues (Bradley and Sprague 1985). Reproduction in rainbow trout is negatively affected by pH values below 5.5, albeit this effect may be moderated by other biological and physical factors (Weiner et al. 1986). A number of additional compounds (such as ammonia, cyanides, hydrogen sulphide, and heavy metals) have a harmful effect on fish, depending on the pH of the water (Avkhimovich 2013). Therefore, fish are likely to experience a variety of impacts under unfavourable pH levels, which, in turn, threaten their survival and development. The pH levels in the study area were ideal for rainbow trout growth (Table 8) (Boyd and tucker 1998; Summerfelt 2000).

Ammonia is present in aquatic environments and is hazardous to all vertebrates. While ammonia may be present in entering waters during aquaculture, the fish create the bulk of ammonia in a fish farm. Ammonia is the principal waste metabolite produced by fish during the breakdown of feed-protein. The fish excrete ammonia through their gills (Evans et al. 2005). Ammonia can also be produced through the decomposition of uneaten food. However, this is a comparatively modest source (Hinshaw & Fornshell 2002). Ammonia exists in equilibrium in two forms in aquatic environments: as unionised ammonia and as ionised ammonium. The equilibrium between $NH_3$ and $NH_4^+$ depends on several parameters, most notably the concentration of hydrogen ions (pH) and temperature. Important is the distribution of total ammonia between $NH_3$ and $NH_4^+$, as $NH_3$ is considered hazardous to vertebrates whereas $NH4+$ is considered

essentially non-toxic at the levels seen in aquaculture systems (Evans et al. 2005).

The ammonia concentrations measured in the study region are listed in Table 8. Although ammonia is not poisonous to fish, the relative amount of unionised ammonia rises as pH and temperature rise, increasing its toxicity (Brinkman et al. 2009). Additionally, a rise in ammonia will raise the pH of the water, causing the pH to exceed acceptable limits. The concentration of DO drops when these (pH or ammonia) parameters rise, and the situation may become dangerous for the health of the fish. Thurston and Russo (1983) determined that the 96-h LC50 for rainbow trout ranged from 0.16 mg/l $NH_3$-N to 1.1 mg/l NH-N and Meade (1985) reported that the 96-h LC50 for rainbow trout was 0.32 mg/l $NH_3$-N.

Regarding ammonia levels in rainbow trout production systems, opinions vary widely. Wedemeyer (1996) suggested no more than 0.02 mg/l $NH_3$, while Hampson (1976) suggested no more than 0.3 mg/L $NH_3$. Haywood (1983) concluded that levels of 0.002 mg/l are safe for salmonids and added that total ammonia levels should be below 1 mg/l. Since the measured values were far lower than the reported toxic/lethal concentrations, the study's waters were appropriate for rainbow trout aquaculture.

In an aquatic environment, ammonium ($NH^4+$) is oxidised to produce nitrite, or $NO_2^-$. According to Colt and Tomasso (2001), nitrite concentrations may rise if ammonia oxidation rates are higher than nitrite oxidation rates or if an inhibitor of the oxidation process, such as ammonia, is present (Russo and Thurston 1991). However, with flow-through systems, which are common in the sector and regularly flush and eliminate organic wastes, nitrite created

on the farm is typically not a concern while raising trout. However, the primary sources of high nitrite concentrations are anthropogenic and come from sewage effluents and agricultural drainage (Wedemeyer 1996).

Nitrate is formed when nitrite is oxidised by bacteria of the genus Nitrobacter (Lewis and Morris 1986). For salmonids, the 96-h LC50 is between 1000 and 3000 mg/l of $NO_3$-N (Wedemeyer 1996). Despite evidence to the contrary, nitrate in flow-through aquaculture systems is rarely considered a risk to rainbow trout in their later stages of life (Russo and Thurston 1991; Tomasso 1994; Wedemeyer 1996). Wedemeyer (1996) recommended a maximum of 1 mg/l, as exposure to eggs might cause developmental difficulties. Thus, the inflow of water with nitrates represents a substantial potential risk during the hatchery stages. The maximum permissible nitrate value for rainbow trout is 20 mg/l (Avkhimovich 2013). It is not necessary to monitor the nitrate concentration in fish farms where the water is sufficiently oxygenated to prevent denitrification. To avoid eutrophication and the excessive growth of plants and algae, which can harm fish, water quality requirements for fish should be installed at the site, as they should be for ammonia (de LG Solbé and Shurben 1989). Table 8 depicts the measured nitrate concentrations in the study area. Based on the values obtained for nitrate, it can be stated that rainbow trout can be safely cultured in the research location because nitrate is not hazardous even at high amounts, which are extremely unlikely to be seen in cold, pure settings like those found there.

Alkalinity, a measurement of the overall concentration of alkaline chemicals dissolved in the water, can protect the water system by buffering against significant and abrupt pH changes. Although alkalinity in and of itself is not harmful to fish, extremely alkaline waters can sometimes pose an issue because they can hinder ammonia excretion and production, which can lead to hazardous amounts of ammonia in the fish (Wright & Wood 1985; Wilson et al. 1998; Wedemeyer 1996). Alkalinity values are given in Table 8. Alkalinity, upper and lower limits are suggested by Wedemeyer (1996): > 20 mg/l (to offer some capacity for buffering against pH extremes) and 100–150 mg/l (as CaCO3) (to ensure that ammonia excretion is not inhibited). Since the study area's waters have sufficient alkalinity, it can be safely recommended for culturing rainbow trout.

Water hardness is principally determined by the concentrations of calcium ($Ca^{2+}$) and magnesium ($Mg^{2+}$) salts (APHA 1998). Water hardness and alkalinity are arguably the most critical measures for biological systems when classifying water for use in aquaculture. For rainbow trout to maintain homeostasis in the freshwater environment, they must control the ion content in their blood. Active transport of ions into the fish takes energy and is accomplished against a concentration gradient. Concentration gradients in

soft water can be quite considerable, reaching up to three thousand times that of blood and water (Wedemeyer 1996), and can consume a significant portion of the dietary energy supply. Active transport of ions from the water through the gills is required to regulate the blood ionic content (Klontz 1991; Wedemeyer 1996;), which requires much energy if the water is soft. Also, the water hardness is a good indicator of a system's calcium and magnesium carbonate buffering capacity, which regulates pH variations, making it useful in aquaculture (Howells 1994). It is an established fact that water hardness regulates pH, which in turn influences the toxicity of chemicals (ammonia, carbon dioxide, heavy metals) to fish. The studied area's hardness levels are shown in Table 8. The values were in line with the specifications suggested for growing rainbow trout.

Phosphate frequently appears in natural waterways as phosphate or the anion ($PO4_3^-$). Because bioavailable phosphate is normally present in the environment at relatively low levels, it is a "growth-limiting" nutrient in most circumstances and a necessary ingredient for life. All energy-producing cellular activities directly require the element phosphorus (P), which is a crucial component of nucleic acids and cell membranes (National Research Council 2011; Roy and Lall 2003). Due to the low phosphate content of natural waters, fish must get P from their diet (Coloso et al. 2001). P deficit or excess may disrupt the synthesis of ATP, nucleic acid synthesis, and the complement of cell membranes, which may result in hunger, brief lethargy, stunted growth, and dark pigmentation (Hardy et al. 1993). Low development, poor feed efficiency, and a lack of bone mineralisation are the main symptoms of P deficiency in most fish (National Research Council 2011). The computed phosphate values for the study region are shown in Table 8. Phosphorus is supplemented through feed in the majority of aquaculture operations, including intensive rainbow trout farming, because it generally exists in a bound state in aquatic systems and cannot be appropriately utilised by fish for their normal functioning.

Water quality parameters for other fish species may be categorised differently based on their physiology and individual requirements. The water quality data did not fluctuate much over the study area and was more or less uniform and within the suitability range for rainbow trout farming (Table 8).

Moreover, it was also observed that out of the nine criteria evaluated through AHP, water temperature, dissolved oxygen and pH were found to be the most essential criteria (Table 4) in rainbow trout farming. According to FAO (2014), water temperature is critical to rainbow trout because it regulates their growth since they are unable to regulate their body temperature on their own. At low temperatures, the growth is slow, but at high temperatures, it is faster, although not specifically for rainbow trout. Nayak et al.

(2018) and Calle Yunis et al. (2020) also found that temperature is the most critical criterion for fish farming site suitability analysis. Also, Boateng et al. (2001) and Boyd and Tucker (1998) believed that fish growth is critically impacted by water temperature and dissolved oxygen and should be considered when setting up fish farms. It is crucial to keep in mind that raising rainbow trout requires a consistent supply of fresh, clean, and oxygen-rich water.

The topography sub-model (Fig. 6) focussed on elevation, slope and LULC of the region, and according to these sub-criteria, the model was distributed into three classes viz., most suitable (939.49 ha; 0.40%), moderately suitable (79,786.85 ha; 34.18%) and least suitable (152,691.70 ha; 65.41%) (Table 7). The elevation is also a critical factor for rainbow trout fish farming, as elevation governs the region's temperature. The higher the elevation, the lower the temperature is a well-known fact. Peters (1988) and Chen et al. (2011) argued that geographical characteristics (latitude and longitude) and elevation were critical for describing a species' range. In the present study, the elevational percentage influence on-site suitability analysis was 30%. Since the region's terrain is highly undulating with varying slopes, elevation and slope are critical for identifying suitable locations for aquaculture siting. Farm layout and pond design are highly dependent on topography. Ideally, the slope of the land should be 2–4% to allow gravity to easily and efficiently fill and drain ponds (FAO, 1995). The slope is the most important criterion (44%) for site suitability analysis in this study. Similarly, Francisco et al. (2019) reported slope as the most critical factor, while Calle Yunis et al. (2020) reported slope as the second most important factor in aquaculture siting.

The fundamental issue in aquaculture site selection is its sustainability. One must anticipate the required environment for aquaculture prior to its implementation and minimise resource usage conflicts with other industries (Hipel et al. 2018). In the present study, LULC percentage influence in site selection was 26%, and the land use classes, such as wasteland, agriculture land, grassland etc., were taken into account in the selection process under different distribution class categories (Table 2). The land use land cover (LULC) dataset depicts the current use and natural resources of the entire study area. In decision-making, the existing or current land use/cover category is crucial because CRZ and CAA regulations specify which categories can or cannot be used for aquaculture. Volcker and Scott (2009) believed that since agriculture and pastures use land with low slope variations, the best candidates were those currently utilised for those activities, which may be easier to work within constructing ponds. Moreover, Little and Muir (1987) also argued that while selecting aquaculture sites, it is essential to consider land use and any agricultural activity already established in

the surrounding area as conditions that favour agriculture generally favour aquaculture also and vice versa.

In traditional flow-through systems, the culture of rainbow trout is predominantly carried out in cemented tanks. When constructing a concrete raceway, it is crucial to understand the strength of the local soil, as it must be able to support the weight of the pond that will be built there (Woynarovich et al. 2011). Francisco et al. (2019) argued that the texture of the soil, specifically its clay content, was also important. Since rainbow trout culture is an intensive farming practice, soil's nitrogen, phosphorus, organic matter, etc., have little relevance as nutrients would be obtained from feed instead of natural productivity (Boyd 1995). Hossain et al. (2007) and Yoo and Boyd (1994) also believed that the loss of water by leakage and infiltration in soils with very high permeability could increase the demand for water and pumping systems.

When it comes to the local reality of the district Tawang, Arunachal Pradesh, the second most important criterion after water quality is infrastructural facilities (32%). Under the infrastructural sub-model (Fig. 7), parameters such as distance to the water source (51%), distance to the hatchery (23%), distance to a road (18%) and distance to the fish market (8%), were considered (Table 6), and model was distributed into three suitability classes viz most suitable (3550.93 ha; 1.5%), moderately suitable (14,745.78 ha; 6.25%) and least suitable (3151.72 ha; 1.34%) (Table 7). Nayak et al. (2018) and Hadipour et al. (2014) have argued that distance to the water source is the most critical criterion for site selection, while Calle Yunis et al. (2020) have reported it to be the second most important factor as the drainage density of the study area, Molinopampa, was very high (0.703 km/km$^2$).

The availability of fish seed in the nearby vicinity is critical for any aquaculture operation. Likewise, road accessibility and market availability to sell farm produce are also important. Thus, to make aquaculture operations viable, it is crucial to consider these factors judiciously. In the present study, the percentage influence of these parameters under the infrastructural sub-model stands at second (23%), third (18%) and fourth (8%) positions. Nayak et al. (2018) considered seed availability in the vicinity more important than market facilities and road accessibility for enhancing fishery development in Central Himalayas. Ssegane et al. (2012), on the other hand, have given more priority to market facilities over farm inputs for modelling the pond-based site suitability for Tilapia and Clarias farming in Uganda. Hossain et al. (2007) argued that road accessibility is more important than the availability of fry and market for tilapia fish farming development in Bangladesh. Calle Yunis et al. (2020) have argued that access to roads is more important than the availability of market facilities and inputs. Thus, site

and location-specific importance exists for these parameters and needs to be addressed very carefully.

The constraint layers like slope class (> 25°), forest area, built-up area, existing water bodies (lakes and rivers), and road network were identified and mapped (Fig. 9). believe that land should be divided into different zones based on suitability score rating. The present study suggests that the study area be divided into the following three zones, i.e. most suitable, moderately suitable and least suitable, based on the suitability of rainbow trout farming. The zoning approach can be helpful to farmers/investors while identifying suitable zone for specific objectives that could benefit them as much as possible (Hossain and Lin 2001).

Ambient climate, pristine cold and abundant waters and ample land availability coupled with the local demand for the produce are comparative advantages of the region. It can, thus, become an investment opportunity to initiate and propagate rainbow trout farming in the region, not only as an activity aimed at catering the local needs but also as possibilities exist for competing with internal and external markets, thereby contributing to the development of the region.

## Conclusion

This study highlighted the utility of a GIS–MCE model to identify the potential sites for cold-water aquaculture development in the Eastern Indian Himalayan region. We developed a GIS–MCE model by considering water quality, topography and infrastructural facilities as well as inputs from experts and stakeholders to identify suitable sites for rainbow trout farming development in district Tawang, Arunachal Pradesh. We found out that the region can be categorised into three zones for rainbow trout farming operations, namely most suitable (340.21 ha; 0.14%), moderately suitable (1810.98 ha; 0.77%) and least suitable (50.70 ha; 0.02%) based on the estimated ecological parameters. Constraint areas constituted approximately 99% of the total geographic area of the study region. Conflicts of aquaculture with other land uses have been a critical issue in most countries, including India, where aquaculture is one of the leading industries. This study demarcated the LULC classes that can be adapted for aquaculture legally at the site selection stage, thereby alleviating the possibility of cross-sectoral conflicts.

Moreover, this model has a framework with criteria to achieve specific objectives, which can be adapted to similar agro-climatic settings within and abroad. The GIS model's significance lies in its ability to assimilate multiple environmental, topographical, and socio-infrastructural criteria within a framework that reflects various spatial scenarios and priorities. It is noteworthy that the parameters considered in this study pertain primarily to the rainbow trout species, but they can also be applied to other cold-water fish species with some modifications. Despite the usefulness of the GIS–MCE model as a tool for selecting sites, uncertainty in extracting more accurate maps limited the final suitability map produced. Despite the present study, the criteria used could change in the future depending on the perspectives and priorities of stakeholders and decision-makers. In light of such elements, the current model may need to be refined further with supplementary elements or even additional adjustments. The authors propose that acquaintance with mountainous regions, long-term location-specific working experience, and stakeholders' interaction are critical variables in designing efficient spatial models for aquaculture.

**Author contributions** PAG: project administration, conceptualisation, resources, methodology, data curation, software, writing—original draft, writing—review and editing; RP: methodology, software, formal analysis, data curation, validation, visualisation; DB: project administration, conceptualisation, resources, formal analysis; KK: visualisation, resources, data curation, formal analysis. GK: resources, data curation, formal analysis. DS: resources, data curation, formal analysis. PKP: investigation, supervision, visualisation, resources, review and editing.

**Data availability** The majority of the data utilised in this study can be obtained without cost from several online databases. Data tiles for both the SRTM DEM and Landsat 8 (OLI) were obtained for free from the USGS Earth Explorer repository. The remaining data used are available within the manuscript.

## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Ethical approval** The authors of this article confirm that they have not undertaken any research involving human subjects or animals.

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